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Modeling relationship between runoff and soil properties in dry-farming lands, NW Iran

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Abstract

The process of transformation of rainfall into runoff over a catchment is very complex and exhibits both temporal and spatial variability. However, in a semi-arid area this variability is mainly controlled by the physical and chemical properties of the soil surface. Developing an accurate and easily-used model that can appropriately determine the runoff generation value is of strong demand. In this study a simple, an empirically based model developed to explore effect of soil properties on runoff generation. Thirty six dry-farming lands under follow conditions in a semi-arid agricultural zone in Hashtroud, NW Iran were considered to installation of runoff plots. Runoff volume was measured at down part of standard plots under natural rainfall events from March 2005 to March 2007. Results indicated that soils were mainly clay loam having 36.7% sand, 31.6% silt and 32.0% clay, and calcareous with about 13% lime. During a 2-year period, 41 natural rainfall events produced surface runoff at the plots. Runoff was negatively (R^2=0.61, $p < 0.001$) affected by soil permeability. Runoff also significantly correlated with sand, coarse sand, silt, organic matter, lime, and aggregate stability, while its relationship with very fine sand, clay, gravel and potassium was not significant. Regression analysis showed that runoff was considerably ($p < 0.001$, R^2=0.64) related to coarse sand, organic matter and lime. Lime like to coarse sand and organic matter positively correlated with soil permeability and consequently decreased runoff. This result revealed that, lime is one of the most important factors controlling runoff in soils of the semi-arid regions.

1 Introduction

Runoff occurs only when the rate of rainfall on a surface exceeds the rate at which water can infiltrate the soil (Schwab et al., 1993; Le Bissonnais et al., 2005). Runoff more commonly occurs in the arid and semi-arid regions, where rainfall intensities are high and the soil infiltration capacity is reduced because of surface sealing, or in paved areas. Runoff generation is an important factor in soil loss (Le Bissonnais et al., 2005) and nutrient movement from soil surface (Lal, 1998; Simard et al., 2000; Ng Kee Kwong et al., 2002), and consequently declining soil productivity and crop yield, particularly in dry-farming lands of semi-arid regions. Some records showed that in semi-arid areas with fine textured soils, runoff can vary between 8% and 49% of the annual rainfall depending on the prevailing conditions (Hensley et al., 2000; Botha et al., 2003). Studies by Morin and Cluff (1980) showed that the most important factors influencing runoff in semi-arid areas were: rainfall intensity; the final infiltration rate of the soil, which is greatly decreased by crusting; the extent to which the soil surface can store water before runoff starts which is described by a parameter termed surface detention; a crusting parameter. Over the last two decades, a large body of knowledge has been built up about the hydrological processes such as runoff in semiarid areas (Yair and Lavee, 1985; Abrahams et al., 1988; Martínez-Mena et al., 1998). These studies show that the runoff-controlling factors in semi-arid catchments are different from those which regulate the hydrology of wetter environments (Lavee et al., 1998; de Wit, 2001). In semi-arid catchments, surface conditions, such as soil crusting and rock pavement (Sole'-Benet et al., 1997) are the most relevant factors. Runoff generation in semi-arid regions is dominated by an infiltration excess mechanism with a short time to final infiltration rates and a fast response due to steep hillslopes with shallow soils, exposed rocks and lack of vegetation (Wheater, 2002; Greenbaum et al., 2006).

The process of transformation of rainfall into runoff over a catchment is very complex, highly nonlinear, and exhibits both temporal and spatial variability (ASCE, 2000a). Modeling of the runoff is the first step for the design and planning of many water resources engineering projects. Many hydrologists devote themselves to develop models to estimate runoff. The process of runoff generation, which involves many mechanisms, is known as a highly complicated and nonlinear phenomenon. Difficulties exist in the modeling of the runoff generation process. Thus, an accurate and easily-used model that can appropriately model the runoff generation process is of strong demand (Lin and Wang, 2007). Recently many models have been developed to simulate this process. These can be categorized as empirical black box, conceptual, and physically based distributed models. Each of these types of models has its own advantages and limitations (ASCE, 2000b). It is evident that information on the factors that control runoff is the first step in modeling runoff. Methods of runoff estimation necessarily neglect some factors and make simplifying assumptions regarding the influence of the others (Schwab et al., 1993).

Factors affecting runoff may be divided into those factors associated with the rainfall i.e. duration and intensity, and those with the watershed (slope, shape and surface storage) and soil (Schwab et al., 1993). Indeed, the rainfall and watershed information alone are not sufficient to compute the runoff value from a catchment as the state of the catchment related to soil properties plays an important role in determining the runoff generation behavior (Yair and Lavee, 1985; Abrahams et al., 1988; Martínez-Mena et al., 1998). It has been proven that not only the patterns of rainfall are highly variable over space and time, soil parameters responsible for runoff generation e.g. infiltration capacity, soil moisture, and aggregate stability are highly variable, too (Seeger, 2007). Theoretical and field studies have also revealed that runoff generation is strongly non-uniform (Loague and Gander, 1990; Jordan, 1994), as a result of the spatial variability of soil infiltration capacities. However, whereas in humid areas this variability is mainly attributed to spatial differences in soil moisture (Troendle, 1985), in semi-arid areas it is mainly controlled by the physical and chemical properties of the soil surface and rainfall characteristics (Lavee and Yair, 1987). Modeling Runoff in semi-arid areas is a challenging task because, many of the hydrological models developed for more humid areas are tuned to a saturation excess mechanism and not to the infiltration excess mechanism that often dominates in dry regions (Faures et al., 1995). In these regions, runoff is formed when the rate of rainfall on soil exceeds the rate at which water can infiltrate the soil. The rate of infiltration of water into the soil depends on several soil properties, particularly physical characteristics of the soil (Ghawi and Battikhi, 1986).

Review of the studies showed that many investigations have been performed on relationship between runoff generation and rainfall parameters (Rajurkar et al., 2004;

Anctil et al., 2006; Boughton, 2006; Jacquin and Shamseldin, 2006; Al-Qurashi et al., 2008; Bahat et al., 2009). Some studies also have focused on effect of physical and hydrological parameters of the watershed in producing runoff (Parsons et al., 1997; Martinez-Mena et al., 1999; Wainwright et al., 2000; Onda et al., 2006). Studies on effect of soil in the runoff generation are mainly related to the influences of antecedent soil moisture (Fitzjohn et al., 1998; Meyles et al., 2003; Castillo et al., 2003; Wei et al., 2007) and soil management systems (Martínez et al., 2006; Gómez et al., 2009) on the runoff generation. Some studies showed that soil surface structure is one of the main factors controlling runoff and subsequent water erosion in cultivated soils and is, as such, a major threat to sustainable agriculture (Farres, 1987; Le Bissonnais et al., 2005; Lecomte et al., 2001). Through the soil structure, the soil water status and the microrelief; the first few millimetres of the topsoil strongly affect infiltration rates and runoff generation (Auzet et al., 2004). According to Skidmore and Layton (1992) the fine particle fraction of the soil plays a very important role in soil crusting processes and that an increase of finer soil particles increases the crust strength. Importance of soil surface seal properties as a main responsible factor in infiltration process and runoff generation has been proven (Bohl and Roth, 1993; Bradford and Huang, 1994). Records by Adekalu et al. (2007) showed that coarse particles of soil have an important role in declining surface runoff. In separate studies on clay loam soils in Australia, Costin (1980) and Lang (1979) reported that 70–75% ground cover was the critical threshold, above which runoff was slight and below which runoff increased rapidly. Many studies showed that adding organic matter to soil resultes a low surface runoff due to an increasing in soil water infiltration capacity (Zehetner and Miller, 2006; Zeiger and Fohrer, 2009). In an investigation Rubio et al. (1997) observed that under similar conditions, the taxonomical and textural characteristics of soil after forest fire are determinant factors in the production of runoff. Effect of some salts such as $CaCO_3$ (lime) and $CaSO_4$ (gypsum) on clay dispersion, infiltration and runoff was well known (Roth and Pavan, 1991). The review of Calvo-Cases et al. (2003) has shown large disparities of final infiltration capacities. Nevertheless, these authors report low runoff coefficients for limestone hillslopes with high infiltration rates under vegetation and the lower ones on areas with rock outcrop.

Almost 39 percent of Iran (642 797 km^2) has a semi-arid climate condition, with an annual precipitation between 200 and 500 mm (Alizadeh, 2003). In these regions about 33% of the annual precipitation loss as surface flows (Rafahi, 1996). Crop production in dry-farming lands of these environments is mostly under rainfed conditions, most of which is marginalized by water stress. Prevention of runoff generation in dry-farming lands from the semi-arid regions is an essential issue to conserve soil productivity and water supply for crop production. Therefore, determining soil properties that influence runoff in dry-farming lands is the first step in the choice of a strategy to control runoff. Limited studies have been done on the modeling runoff in Iran. More studies have focused on the effect of land use change on runoff generation (Sadeghi et al., 2004; Saadati et al., 2006), influencee of grazing on soil infiltratbility and runoff (Eskandari et al., 2004), application of the hydrological model in estimating runoff (Rostamian et al., 2008), and modeling runoff based on geomorphologic properties (Abdollahi et al., 2003). There are relatively little studies which have performed on effect of soil properties in the runoff generation in semi-arid environments in Iran. Some these studies showed that the runoff generation can be affected by soil particles (Raeesiyan, 1996) and surface gravel (Javadi et al., 2004). However, there is no quantity study to predict runoff in dry-farming lands of the semi-arid regions in Iran. The objectives of this work are to quantify the impact of soil physicochemical properties on runoff generation and develop a empirical model for predicting runoff in dry-farming lands from semi-arid regions.

2 Materials and methods

2.1 Study area

The study was carried out in a semi-arid area of NW Iran located in Hashtroud township (southern part of East Azarbyjan province) from March 2005 to March 2006. The study zone was 900 km^2 in area located between 37°18′49′′ and 37°35′0′′ N latitude, and 46°46′5′′ and 47°6′5′′ E longitude (Fig. 1). The climate is semi-arid with an average annual precipitation of 322 mm, mostly falling in the winter, autumn and spring and a mean annual temperature of 13 °C. Agricultural soils located mostly in 5–15% slopes and mainly are utilized for wheat dry farming. The soils have low organic matter (about 1%) and are mainly calcareous with a moderate value of total carbonates (Hakimi, 1986). The field observation showed that cultivation in slope direction is a main factor in producing surface runoff and so declining crops yield in dry-farming lands.

2.2 Field study

To measurement of surface runoff, plots were installed in 36 square grids with a dimension of 5 km×5 km. In each grid, a dry farming land in a south slope 9% was considered. Study lands were plowed in slope direction and harrowed to provide a smooth uniform (Rejman et al., 1998) on February 2005. In each land, three unit plots with 1.83-m wide and 22.1-m long (Wischmeier and Smith, 1978) with 1.5 m spacing were installed on March 2005. Runoff-collecting installations consisted of gutter pipes, pipes and 70-l tanks (Rejman et al., 1998) were established at the lower parts of the plots. After each natural rainfall producing runoff at each plot, total runoff volume generated in the collecting tank was measured. Runoff was then mixed thoroughly and a 0.5-l sample was taken to determination of water volume (Guy, 1975; Hussein, 2007). In the laboratory, the runoff samples were weighed and evaporated on a hot plate then weighed again to determine sediment concentration (Guy, 1975). Water loss of each plot was determined based on multiplying total runoff volume by volumetric percentage of water in the sample. Annual surface runoff also was obtained from summation of total surface runoffs produced in different natural rainfall events for each year. Runoff coefficient (runoff factor) of each plot was also obtained from proportion of runoff depth (mm) per unit of rainfall depth (mm).

2.3 Determination of rainfall properties

Rainfall data were taken from five rainfall gauges stations installed in the study area (Fig. 1). Four standard rainfall gauges located in the grids 2, 10, 27 and 30 were used to manually measure the depth of rain after each event. An automatic rain gauge belonging to Irrigation Office of Hashtrood located in the grid 17 was also used to determine intensity of rainfall events. On the basis of recording rain gauge data of the meteorological station in grid 17, the rainfall intensity and I_{30} (the maximum 30-min intensity), and rainfall energy of rainfall events was obtained for a 2-year period. The rainfall energy computed using the energy equation as follow (Wischmeier and Smith, 1978):

$$\mathrm{KE} = 210.3 + 89 \log_{10} I \qquad (1)$$

where I is the rainfall intensity ($\mathrm{cm\,h^{-1}}$) and KE ($\mathrm{J\,m^{-2}\,cm^{-1}}$) is kinetic energy per unit rainfall height (cm). The kinetic energy, E ($\mathrm{J\,m^{-2}}$) was obtained by multiplying KE into the rain depth (cm). Rainfall erosivity index ($\mathrm{EI_{30}}$) which is a major causal factor of soil erosion (Angulo-Martínez et al., 2009) was obtained by multiplying E into I_{30} ($\mathrm{mm\,h^{-1}}$) and accordingly was calculated as $\mathrm{MJ\ mm\,ha^{-1}\,h^{-1}}$ unit. The annual rainfall erosivity factor or R ($\mathrm{MJ\ mm\,ha^{-1}\,h^{-1}}$) was ultimately calculated by the summation of the $\mathrm{EI_{30}}$ values of different rainfall events occurred in the first and second year.

2.4 Determination of soil properties

To determination of soil properties influencing runoff, soil samples (0–30 cm depth) were taken randomly from three locations within each plot before plowing. Then, the samples of each plot were mixed together and a representative sample was provided. After being dried, the soil samples were grounded to pass a 2 mm sieve and stored in sealed polyethylene bags in a cool and dry place until the chemical analysis in the laboratory. The particle size distribution consisted of coarse sand (0.1–2 mm), very fine sand (0.05–0.1 mm), silt (0.002–0.05) and clay (<0.002 mm) was determined by the Robinson's pipette method (SSEW, 1982). Gravel (2–8 mm) was determined using the weighting method (Gee and Bauder, 1980). The total soil organic carbon was measured by the Walkley-Black wet dichromate oxidation method (Nelson and Sommers, 1982) and converted to organic matter through multiplying by 1.724. To determine lime amount, the total neutralizing value (TNV) on the basis of calcium carbonate was measured using acid acetic volume consumed to neutralize carbonates (Goh et al., 1993). The available potassium content was also measured with the ammonium acetate extraction method (Knudsen et al., 1982). The soil structure was determined based on the size and shape of aggregates according to the Wischmeier and Smith's (1978) procedure. The aggregate stability was determined using the wet-sieving method based on the mean weight diameter (MWD) as proposed by Angers and Mehuys (1993). The water-stable aggregates were determined by placing 100 g aggregates with diameter larger than six mm on the top of sieves set and moved up to down in a water cylinder for one minute. The soil permeability was determined in the field based on the final infiltration rate for each study plot by measuring the one-dimensional water flow into the soil per unit time by double-ring infiltrometer (Bouwer, 1986) at four to six replications. The infiltration measurements were carried out at the end of the dry season (in July 2005) in order to exclude the influence of different initial moisture contents as described by Turner and Summer (1978).

2.5 Statistical analysis

Data were assessed for normality using the Kolmogorov-Smirnov test. Factors influencing runoff was extracted based on bivariate correlation between runoff and soil properties using Pearson's method (Soka and Rohlf, 1981). A stepwise multiple regression analysis was utilized to formulate an equation to predict runoff generation based on the soil properties.

3 Results

3.1 Rainfall properties

Ninety seven natural rainfalls occurred in the study area during the 2-year study period. Table 1 shows mean characteristics of the natural rainfall events from March 2005 to March 2007. Out of 97 rainfall events, 41 rainstorms produced runoff and sediment (soil loss) at the unit plots of the study area (Table 2). The rainfall erosivity index (EI_{30}) varied from 1.077 to 73.402 MJ mm ha^{-1} h^{-1}, with an average of 15.444 MJ mm ha^{-1} h^{-1}. The mean annual erosivity factor (R) was also identified to be 334.543 MJ mm ha^{-1} h^{-1} year^{-1}. The mean depth of rainfalls causing sediment in the rain gauge stations located in grids 2, 10, 17 and 30 were 7.22, 6.59, 6.98 and 6.84 mm, respectively. There was no significant difference among the rainstorms depth values recorded by different rain gauge stations (F=0.027, P-value=0.994).

3.2 Runoff production

The results are summarized in Table 3. Mean surface runoff produced at 36 study plots was varied from 3.39 mm yr^{-1} (33.90 m^{3} ha^{-1} yr^{-1}) to 11.92 mm yr^{-1} (119.20 m^{3} ha^{-1} yr^{-1}) with an average of 8.09 mm yr^{-1} (80.89 m^{3} ha^{-1} yr^{-1}). Runoff coefficient of the plots was ranged from 0.02 mm mm^{-1} to 0.08 mm mm^{-1} with an average of 0.06 mm mm^{-1}. Runoff generation at the plots in different rainstorms varied due to variations of rainfall properties. As shown in Fig. 2 despite a significant correlation between average runoff produced in the study area with the rainfall depth (R^2=0.73, $p<0.001$), maximum 30-min intensity of rainfalls (R^2=0.73, $p<0.001$) it had the highest correlation (R^2=0.81, $p<0.001$) with rainfall erosivity index (EI_{30}). With an

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increasing in the rainfall erosivity index, runoff volume remarkably increased. There is no significant correlatyion between runoff and rainfall intensity (R^2=0.41) (see also the supplementary material at http://www.hydrol-earth-syst-sci-discuss.net/7/2577/2010/hessd-7-2577-2010-supplement.pdf).

3.3 Soil properties

Since there was no significant difference in rainfall properties (depth) among the rain gauge stations, the spatial rainstorms distribution was uniform. Thus, difference in runoff generation at the unit plots was directly depended on the soil properties. As shown in Table 4, soil textures were mainly clay loam having 36.7% sand, 31.6% silt and 32.0% clay. Soils had low organic matter (1.1%) and were calcareous (limy) containing 13% calcium carbonate equivalent (lime). The gravel and potassium amounts were 10% and 315 mg kg^{-1}, respectively. Aggregates were mainly granular with a mean diameter of 5 mm. The water- aggregate stability of the soils was very low; the mean weight diameter (MWD) value ranged between 0.27 and 1.91 mm with an average of 1.13 mm. The soil permeability value on the basis of the final infiltration rate varied between 1.4 and 5.8 cm h^{-1} with an average value of 3.5 cm h^{-1}. Statistical distributions of the different soil properties were normal.

3.4 Relationship between runoff and soil properties

Mean annual runoff value at the study plots was between 137.12 and 482.07 l, with an average of 327.16 l for a 2-year period. Based on the results, the annual runoff produced at the study plots significantly ($p < 0.001$, R^2=0.61) influenced by permeability described as final infiltration rate. With a increasing in the final infiltration rate, runoff generation linearly decreased (Fig. 3).

Since measurement of the final infiltration rate using double rings in the filed is relatively difficult and consuming time, there is a need to estimation of runoff using easily-measurable soil properties. Table 5 shows the correlation matrix of runoff

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and physicochemical soil properties in the study area. Results indicated that runoff significantly correlated with coarse sand ($p < 0.001$), silt ($p < 0.05$), organic matter ($p < 0.001$) and lime ($p < 0.05$), aggregate stability ($p < 0.001$), while its relationship with very fine sand, clay, gravel and potassium was not significant. Coarse sand, organic matter and lime positively correlated with soil permeability and consequently decreased runoff in study area.

Multi-regression analysis of the relationship between runoff and its effective soil properties revealed that runoff is significantly ($p < 0.001$, R^2=0.64) related to coarse sand, organic matter and lime. In fact, the easily-measurable soil properties could explain 64% variations of runoff in the study area. Table 6 shows the multi-regression analysis of runoff and the easily-measurable soil properties influencing it. Coarse sand, organic matter and lime at the statistical level of 0.001, 0.01 and 0.01 negatively influenced runoff in the study area, respectively.

Therefore an empirical model was extracted from the multiple regression analysis:

$$R = 174.812 - 1.842\mathrm{CS} - 36.566\mathrm{OM} - 1.524\mathrm{Li} \tag{2}$$

Where R is the runoff volume ($\mathrm{m}^3\,\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$), CS is coarse sand (%); OM is organic matter (%) and Li is lime/total carbonates as calcium carbonate (%) in soil surface sample.

4 Discussion

Analysis of forty one rainstorms caused runoff indicated that out of the rainfall parameters (depth, intensity, maximum 30-min intensity and erosivity index), the rainfall erosivity index (EI_{30}) had the highest correlation with runoff generation in the study area. This result accords with Onda et al. (2006), who found that surface runoff has a good correlation with the rainfall energy. Runoff generation in thirty six study plots also related to soil permeability (final infiltration rate). This result is in accord with Gómez et al. (2001), who found that approximately 50% of variability of runoff in fallow plots can be explained by the final infiltration rate. Many authors noted that closely related to the runoff generation mechanisms is the infiltration capacity of the soils. Indeed, infiltration capacity which was determined based on the final infiltration rate, is the most important factor controlling runoff in the soils (Brakensiek and Rawls, 1994; Roth, 2004).

Independent soil properties consist of mineral particles, organic matter and lime considerably influenced runoff generation in the study area. Coarse sand, organic matter and lime contrary to silt positively affected soil permeability and consequently reduced runoff. Thus, variations of these parameters in the study soils could remarkably influence on generation of runoff in the study area. Studies by Brakensiek and Rawls (1994); Maestre and Cortina (2002); Roth (2004) indicated that spatial variability of the soil infiltration capacity is related to the high spatial variability of soil properties (structure, organic matter content, antecedent soil moisture, etc.) that affect the runoff generation in the hillslopes.

Aggregate stability as a dependent soil property was an important factor controlling runoff in the study area. This result agrees with Cammeraat and Imeson (1998), Barthès and Roose (2002) who confirmed that aggregate stability is a relevant indicator of runoff and soil susceptibility to water erosion in semi-arid environments. Nevertheless, effect of the aggregate stability in decreasing runoff was not due to its influence in enhancing soil permeability. Because, there was no significant correlation between aggregate stability and soil permeability. This result is contrary to Lal and Shukla (2004) who noted that soils that have poor structure, leading to surface sealing of pores and crusting, and consequently less infiltration and high runoff. In this investigation, permeability of soils was measured based on final infiltration rate in soil profile and in this reason it was not affected by the aggregate stability which was measured in soil surface samples. Soil structure disruption by raindrop impact could be reduced due to a presence of the stable aggregates in soil surface and so water can enter to soil with a relatively high rate at initial times of starting rainfall. In this reason, increasing aggregates stability of surface soil can decline runoff generation without it could affect the final infiltration rate.

Results showed that runoff is significantly influenced by soil particles i.e. coarse sand and silt. This result agrees with Malik et al. (1987) who found that runoff significantly related to soil texture. Effect of coarse sand in enhancing soil permeability and in consequence reducing runoff agrees with Santos et al. (2003) who found that in sandy soils due to presence of macro pores, rate of water enter to soil is higher than of fine textured soils and so generation of runoff is lower than them. Organic matter has been recognized as important binding and bridging agent in enhancing a soil's structural stability, infiltration capacity, and in consequence reducing runoff (Hartanto et al., 2003; Fernández er al., 2006; Zhang et al., 2007). Based on the results (Table 6) lime explained about 30 per cent of the runoff generation in soils of the study area. This result revealed that lime is an important factor controlling runoff in soils of semi-arid regions. In these soils, Ca^{2+} cation binds soil particles and improves the aggregates stability in soil profile length. With an increase in aggregates stability of the soil surface, infiltration rate increases and consequently the runoff generation considerably declines. This result accords with Pepper and Morrissey (1985) who found that runoff is negatively related to the exchangeable calcium percentage. Although clay considerably correlated with aggregate stability, its effect on the runoff was not considerable. This result is not in line with Pepper and Morrissey (1995) who found that runoff is positively affected by clay. Effect of gravel on runoff also is not in accord with Mathys et al. (2005) who indicated that the infiltration rate is increased by the gravel cover of soil surface in the Black Marls.

Considering importance of water conservation in the dry-faming lands to supply plant requirement and keep soil productivity, modeling runoff is the first step in the choice of a strategy to control runoff. Although the final infiltration rate was the most important factor influencing runoff in the study soils, due to some difficulties in its field measurement, developing a simple and practical model to predict runoff in the study area was necessary. Coarse sand, organic matter and lime as the easily-measurable soil properties influencing infiltration and runoff were used to establish a linear model. Using this empirical model can predict runoff generation from the dry-farming lands in the semi-arid regions where soil and rainfall properties are similar to them in the study area.

5 Conclusions

Modeling of the runoff is the first step for the design and planning of many water resources engineering projects. Limited studies have been performed on modeling runoff in the semi-arid regions in Iran. This study was conducted in an agricultural zoon with 900 km^2 in area in Hashtroud, NW Iran to determinate soil properties affecting runoff and modeling it based on easily-measurable soil properties. Runoff volume was measured at the runoff plots installed in thirty six dry-farming lands under natural rainfall events from March 2005 to March 2007. Based on the results, soils were mainly calcareous containing 13% lime. Out of 96 natural rainfall events, 41 events produced surface runoff on the plots. Runoff was negatively ($R^2 = 0.61$, $p < 0.001$) affected by soil permeability. Runoff also significantly correlated with coarse sand, silt, organic matter, lime and aggregate stability, while its relationship with very fine sand, clay, gravel and potassium was not significant. Regression analysis showed that runoff was negatively ($p < 0.001$, $R^2 = 0.64$) related to coarse sand, organic matter and lime. Lime positively correlated with the aggregate stability and soil permeability, and in consequence decreased runoff generation at the plots.

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Table 1. Mean characteristics of the natural rainfall events between March 2005 and March 2007.

Rainfall characteristic	Mean	StD
Duration (h)	1.80	1.54
Depth (mm)	4.13	4.14
Intensity (mm h^{-1})	2.76	2.55
Maximum 30-min intensity, I_{30} (mm h^{-1})	4.88	4.99
Erosivity index, EI_{30} (MJ mm ha^{-1} h^{-1})	6.76	13.78

Table 2. Characteristics of the rainstorms lead to runoff at the plots between March 2005 and March 2007.

Event no.	Duration (h)	Depth (mm)	Intensity (mm h^{-1})	Maximum-30 min intensity (mm h^{-1})	Erosivity index ($\text{MJ mm ha}^{-1}\text{ h}^{-1}$)
1	1.15	2.55	2.21	3	1.17
2	1.36	3.65	2.68	3.2	1.88
3	3.4	13.7	4.03	15.2	36.64
4	1	2.7	2.7	3	1.3
5	1.3	4.8	3.7	4.8	3.98
6	1.1	3.7	3.36	5.4	3.38
7	6.98	17.85	2.56	7.6	21.55
8	0.7	2.8	4	5.4	2.66
9	1.5	8.35	5.58	8.4	13.2
10	0.71	2	2.82	3.8	1.23
11	0.73	2.5	3.42	4.8	2.04
12	1.15	4.2	3.65	5	3.62
13	1.18	11.9	10.08	21.8	54.63
14	0.9	12.4	13.78	22.8	62.88
15	1.6	8.1	5.06	25	37.37
16	2.1	12.5	5.95	13	30.99
17	1.3	10.4	8	12.2	25.61
18	0.5	3.5	7	7	4.82
19	0.77	1.9	2.47	3.6	1.08
20	1.38	15.3	11.08	22.4	73.4
21	0.65	4	6.15	6.8	5.22
22	0.58	2.4	4.13	4.6	1.95
23	4	9.3	2.32	4.4	6.35
24	0.84	5.3	6.31	8.2	8.36
25	1.67	4.25	2.54	5.2	3.47
26	3.17	6.7	2.11	4.2	4.22
27	1.61	12.7	7.89	14.46	36.92
28	1.5	4.2	2.8	5	3.38
29	1.25	3.3	2.64	4	2.1
30	1.83	5.6	3.6	6	5.74
31	2.38	8.1	3.4	7.4	10.1
32	1.36	4	2.94	4.2	2.74
33	1.34	3.4	2.54	4	2.14
34	1.86	4.8	2.58	7.6	5.76
35	1.8	6.8	3.78	6.6	7.75
36	0.5	4.1	8.2	8.2	6.81
37	3.5	18.7	5.35	13	45.22
38	0.5	4.6	9.9	9.8	9.46
39	0.5	2	4	4	1.4
40	2.15	14.3	6.65	12.4	34.48
41	1.77	8.1	4.56	9.6	13.98

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Table 3. Mean runoff generated by forty one natural rainstorms at the runoff plots in thirty six dry-farming lands in a 2-year study period from March 2005 to March 2007.

Plot No.	Mean runoff (mm yr^{-1})	StD	Runoff coefficient (mm mm^{-1})	Plot No.	Mean runoff (mm yr^{-1})	StD	Runoff coefficient (mm mm^{-1})	Plot No.	Mean runoff (mm yr^{-1})	StD	Runoff coefficient (mm mm^{-1})
1	9.38	0.37	0.06	13	9.94	0.71	0.07	25	10.35	0.51	0.07
2	9.50	0.27	0.07	14	9.48	0.44	0.07	26	6.59	0.14	0.05
3	9.14	0.49	0.06	15	10.02	0.06	0.07	27	4.92	0.6	0.03
4	8.81	0.45	0.06	16	4.61	0.52	0.04	28	11.06	0.25	0.08
5	11.38	0.26	0.08	17	6.00	0.27	0.04	29	9.12	0.33	0.06
6	4.20	0.44	0.03	18	9.51	0.42	0.07	30	8.65	0.4	0.06
7	6.93	0.49	0.05	19	9.96	0.5	0.07	31	6.67	0.33	0.04
8	5.43	0.57	0.04	20	7.34	0.24	0.05	32	3.39	0.19	0.03
9	10.47	0.36	0.07	21	6.57	0.24	0.05	33	6.87	0.35	0.05
10	10.84	0.65	0.07	22	6.56	0.6	0.05	34	7.20	0.41	0.05
11	11.92	0.16	0.08	23	8.74	0.21	0.06	35	8.13	1.00	0.06
12	5.99	0.24	0.04	24	7.32	0.53	0.05	36	8.19	0.55	0.06

Table 4. Physical and chemical soil properties in the study area.

Soil property	Mean	StD
Coarse sand	18.9	5.3
Very fine sand	17.8	3.2
Silt	31.5	7.1
Clay	31.8	5.7
Gravel	9.9	2.4
Organic matter	1.1	0.2
Lime/carbonates (%)	12.7	5.2
Potassium (mg kg^{-1})	314.7	25.4
Structure stability in water, MWD (mm)	1.13	0.44
Final infiltration rate (cm h^{-1})	3.5	1.2

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Table 5. The correlation matrix of runoff and physicochemical soil properties in the study area.

	CS	VFS	Si	Cl	Gr	OM	Li	Pot	AS	Per	R
CS	1										
VFS	0.224	1									
Si	−0.742[a]	−0.197	1								
Cl	−0.179	−0.500[b]	−0.400[c]	1							
Gr	0.028	−0.007	0.024	−0.058	1						
OM	0.268	−0.307[c]	−0.228	0.208	0.165	1					
Li	−0.001	−0.558[a]	0.174	0.028	−0.030	0.046	1				
Pot	−0.072	−0.046	−0.177	0.309[c]	0.093	0.059	−0.092	1			
AS	−0.175	−0.670[a]	−0.123	0.705[a]	−0.091	0.293	0.481[b]	0.217	1		
Per	0.761[a]	−0.047	−0.553[a]	−0.069	0.091	0.541[b]	0.295[c]	0.080	0.134	1	
R	−0.558[a]	0.231	0.419[c]	−0.093	−0.088	−0.565[a]	−0.390[c]	−0.084	−0.467[a]	−0.777[a]	1

CS: coarse sand; VFS: very fine sand; Si: silt; Cl: clay; Gr: gravel; OM: organic matter; Li: lime (carbonates); Pot: potassium; AS: aggregate stability (mean weight diameter of stable aggregates in wet-sieving method); Per: permeability (final infiltration rate); R: runoff

[a] Correlation significant at $p < 0.001$; [b] Correlation significant at $p < 0.01$; [c] Correlation significant at $p < 0.05$

Table 6. The multi-regression analysis of relationship between runoff and the easily-measurable soil properties influencing it.

Model variable[a]	Unstandardized coefficients		Standardized coefficients	t-level	P-level
	Model coefficients	Standard error			
Constant	174.812	12.879		13.574	$p < 0.001$
CS	−1.842	0.461	−0.443	−3.994	$p < 0.001$
OM	−36.566	9.456	−0.429	−3.867	$p < 0.01$
Li	−1.524	0.440	−0.371	−3.465	$p < 0.01$

[a] CS: coarse sand; OM: organic matter; Li: lime (carbonates)

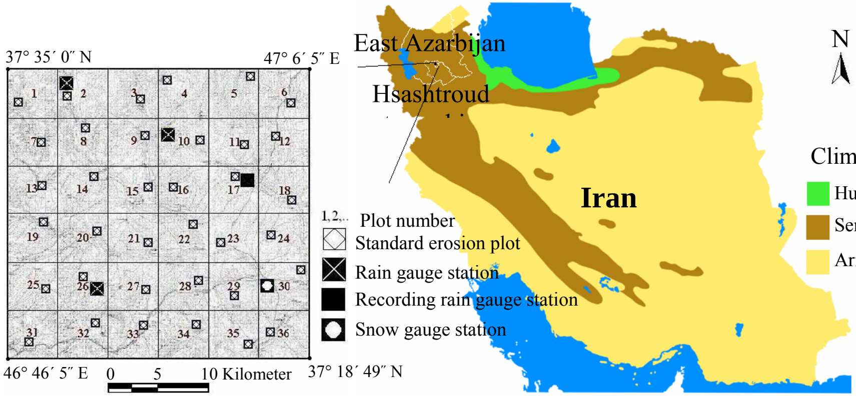

Fig. 1. Location of the study area, rainfall gauge stations and unit plots used for measuring surface runoff.

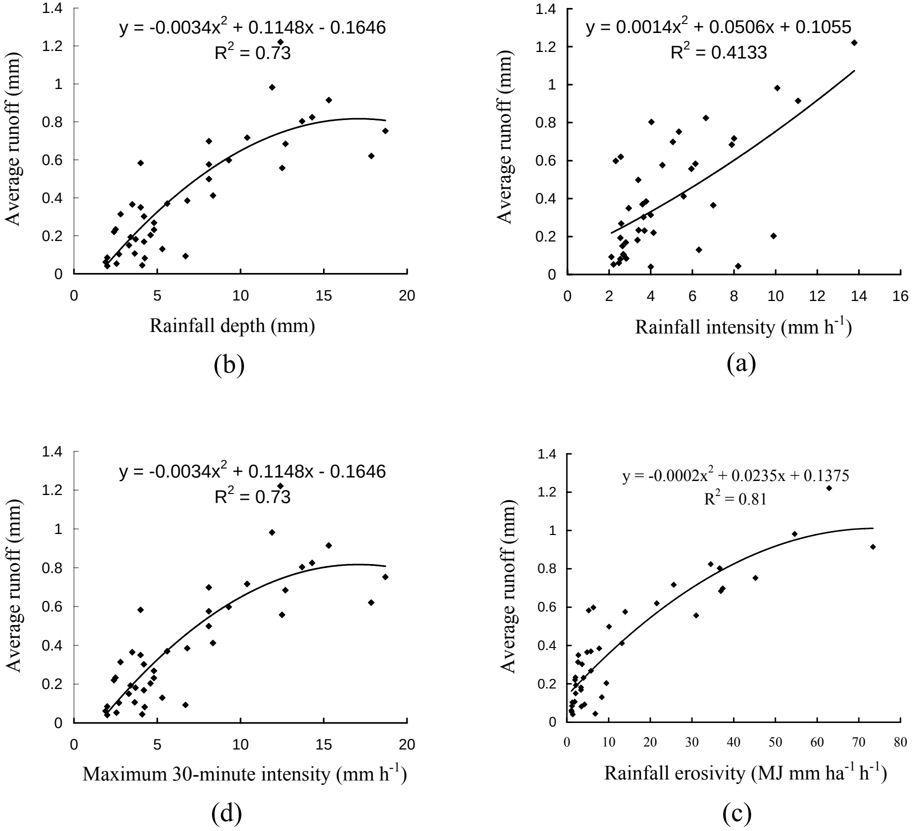

Fig. 2. Relationship between runoff and rainfall erosivity index (EI_{30}) for 41 rainstorms occurred during a 2-year study period in the study area.

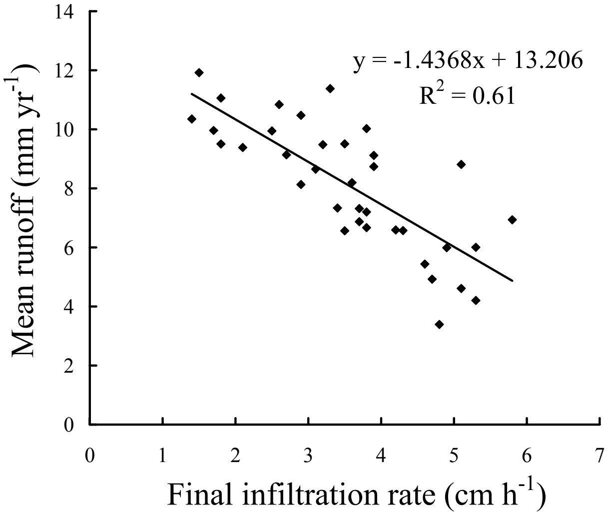

Fig. 3. Relationship between mean annual runoff and final infiltration rate in the study area.